REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER TD 7289	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) TRANSIENT RESPONSE OF VOLUMETRIC SOURCES AND LINE ARRAY SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Paul D. Koenigs and Peter R. Stepanishen (URI)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS New London Laboratory Naval Underwater Systems Center New London, Connecticut 06320		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS A70215 61152N ZR0000101
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 29 November 1984 13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Continuous arrays	Line arrays	Scanned arrays
Distributed arrays	Localization	Steady state
Focused arrays	Nearfield response	Transient
Imaging	Parametric array	Volumetric arrays
Impulse response		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document contains the slide presentation entitled "Transient Response of Volumetric Sources and Line Array Systems," given at the 108th meeting of the Acoustical Society of America, 8-12 October 1984, in Minneapolis, Minnesota.

An impulse response approach to evaluate the transient response of volumetric sources and line arrays with beamformers is presented. A spatially and time-dependent impulse response function resulting from either a continuous

20. Continued:

or discrete distribution of sources with amplitude shading and arbitrary time delays is defined. The transient pressure at a field point is then obtained by convolving the time derivative of the impulse response with an excitation waveform. The characteristics of the impulse response for discrete steered and/or focused line array systems are first presented and related to the geometry of the array and beamformer. The characteristics of the impulse response for continuous line arrays or volumetric sources with spatially dependent amplitude and initial excitation times are then presented and related to the geometry of the source, speed of propagation within the array and media, and the location of the field point. Several applications and numerical results for volumetric sources and line array systems are presented.

NUSC Technical Document 7289
29 November 1984

Transient Response of Volumetric Sources and Line Array Systems

A Paper Presented at the 108th Meeting of the Acoustical Society of America, 8-12 October 1984, Minneapolis, Minnesota

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PREFACE

This document was prepared under NUSC Project No. A70215, "Transient Response of Multidimensional Arrays," Principal Investigator, Paul D. Koenigs; sponsored by the NUSC in-house Independent Research Program under Program Element 61152N, Navy Subproject No. ZR0000101, Gary Morton, Program manager, Director of Navy Laboratories.

REVIEWED AND APPROVED: 29 November 1984

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TRANSIENT RESPONSE OF VOLUMETRIC SOURCES AND LINE ARRAY SYSTEMS

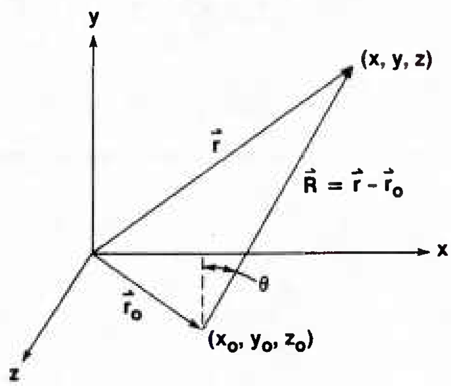
First viewgraph, please (1).

- **DISCRETE LINE ARRAY SYSTEM**
- **CONTINUOUS LINE ARRAY SYSTEM**
- **FREQUENCY FOCUSED AND SCANNED ARRAY**
- **VOLUMETRIC ARRAY**

Viewgraph 1

Although considerable work has been devoted to the analysis of the steady state response of line arrays, less effort has been devoted to a systematic analysis of the transient response of these arrays for wideband signals. The subject of this talk is the extension of the impulse response technique to free field discrete line array systems with line elements and time delay beamformers. We will examine some relatively simple discrete and continuous array systems before showing the transient response of a complex frequency focused and scanned array system obtained by the impulse response technique. We will then show how the technique may be easily extended to investigate the field of a volumetric array that simulates the characteristics of a transient parametric array system.

-- Next viewgraph, please (2). --



(1) $$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = -q(\vec{r}, t)$$

(2) $$p(\vec{r}, t) = \varrho\,\frac{\partial\phi(\vec{r}, t)}{\partial t}$$

(3) $$\phi(\vec{r}, t) = \int_0^t q(t_o)\,dt_o \int \frac{\delta\left(t - t_o - \frac{|\vec{R}|}{c}\right)}{4\pi|\vec{R}|}\,dr_o$$

Viewgraph 2

Consider the problem of determining the time-dependent pressure at a spatial point, r, resulting from a specified spatial and temporal velocity distribution of an array of sources in an ideal fluid of density, ρ, and acoustic propagation speed, c. The inhomogeneous wave equation formulated in terms of a velocity potential, ϕ, and source term, Q, is given by equation 1. The pressure may then be obtained from the velocity potential by applying equation 2. The solution to the wave equation, using a Green's function approach for an unbounded medium and when the source term is independent of its location, is given by equation 3.

-- Next viewgraph, please (3). --

DEFINE

$$h(\vec{r}, t - t_o) = \int_V \frac{\delta(t - t_o - \frac{|\vec{R}|}{c})}{4\pi|\vec{R}|}\, dv$$

THEN

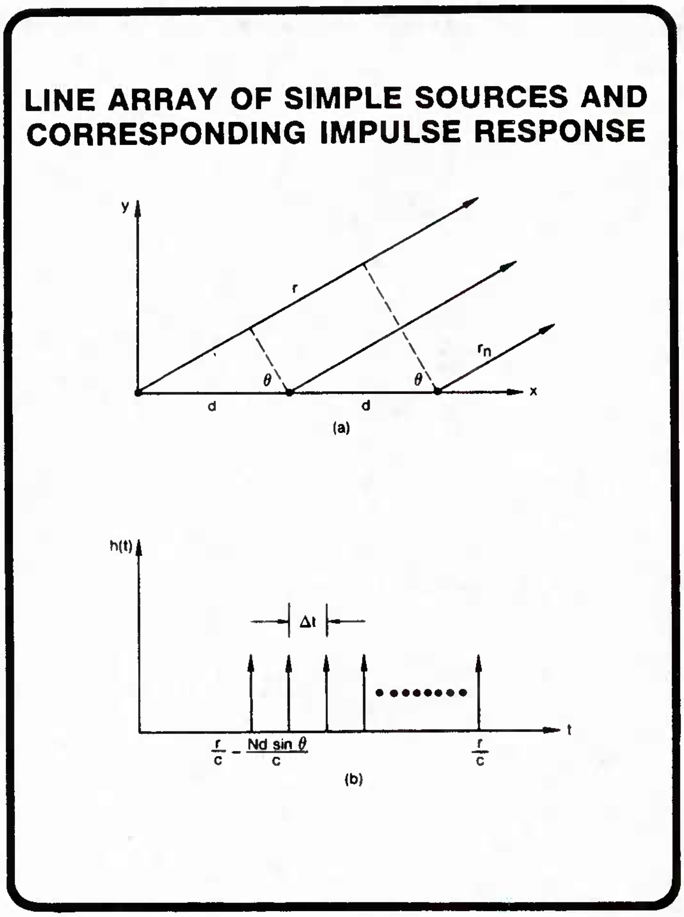
$$\phi(\vec{r}, t) = q(t) * h(\vec{r}, t)$$

$$p(\vec{r}, t) = \varrho \frac{\partial}{\partial t}\left\{q(t) * h(\vec{r}, t)\right\}$$

Viewgraph 3

We now define a spatial impulse response h of r and t. This response function is for a point in space resulting from a distributed source excited at time t_o. In the equation, t_o is an excitation time and may be related to a time-delay beamformer. The quantity R over C is related to the problem geometry and is simply a travel time between the source and spatial point of interest. The velocity potential may then be expressed as a convolution. We can then write an expression for the pressure in terms of a convolution of a source q of t and a spatial impulse response h of t.

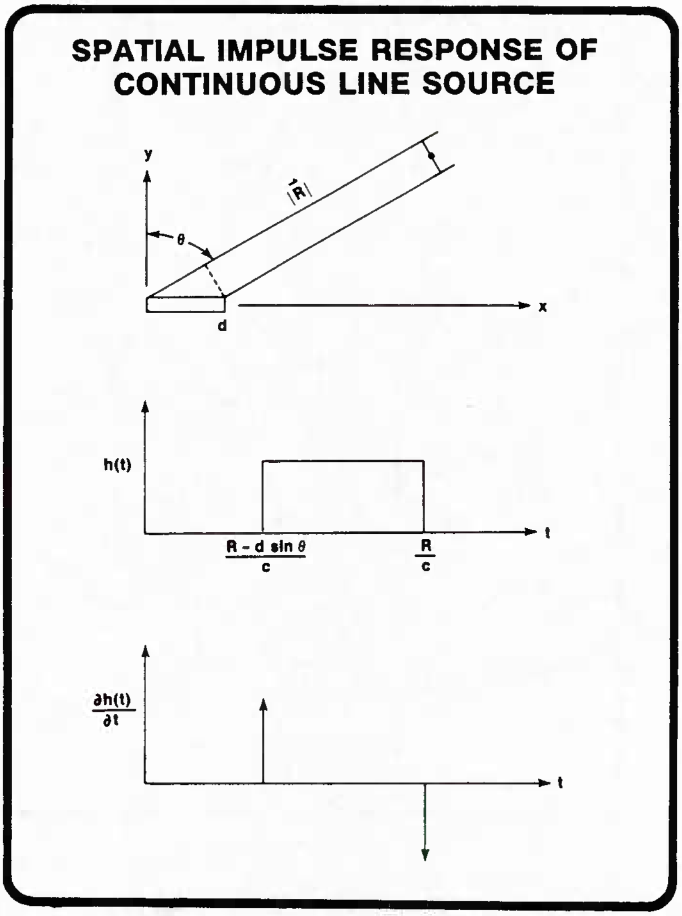
-- Next viewgraph, please (4). --



Viewgraph 4

The impulse response at a field point resulting from a simple source is merely an impulse. A straightforward extension of the simple source to a line array consisting of N + 1 simple sources located a distance, d, apart is illustrated in the upper part of this viewgraph. When all sources are excited simultaneously, the farfield impulse response is simply a series of impulse functions beginning at a time corresponding to the travel time to the nearest element. The train of impulses ends at a time corresponding to the farthest array element and the separation between each impulse is simply dependent on the angle, θ, the interelement spacing, d, and speed of propagation, c.

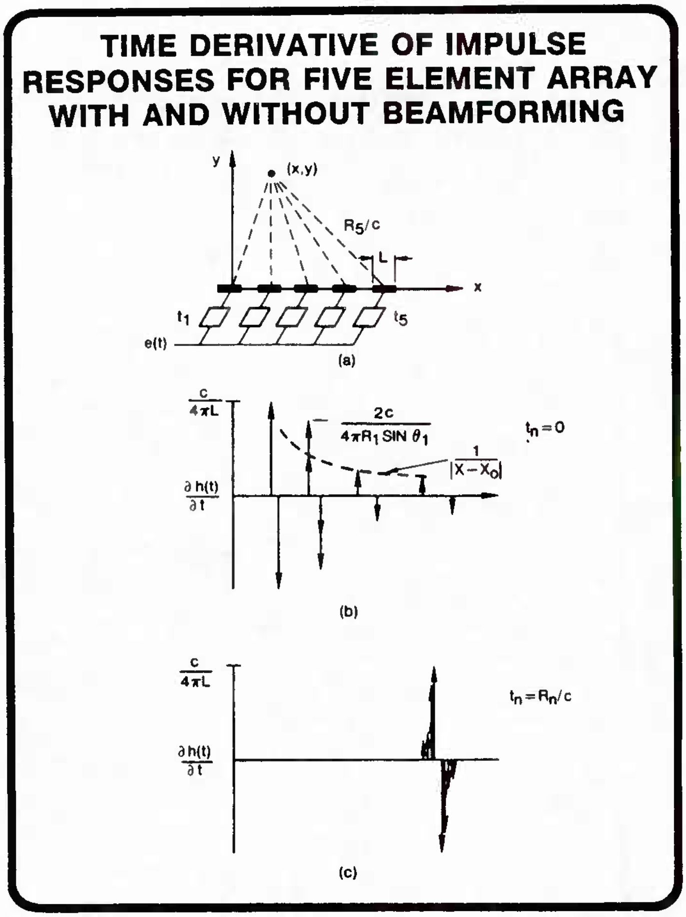
-- Next viewgraph, please (5). --



Viewgraph 5

When the general source distribution in space is such that it can be represented as a continuous line source, a closed form solution for the impulse response may be formed by a linear superposition of simple sources. We first consider the case when the field point is in the farfield and outside the region defined by X = d, as shown in the upper section of viewgraph 5. The impulse response in this case is simply a boxcar function beginning at a time corresponding to the nearest end of the source and ending at a time corresponding to the farthest edge. The spatial impulse response for a complex array may have many such overlapping boxcar functions. Because it is difficult to depict overlapping boxcar functions, we have decided to display the time derivative of the impulse response when appropriate. A sample of this is shown at the bottom of this viewgraph. A positive impulse corresponds to the leading edge and the negative impulse corresponds to the trailing edge of the spatial impulse response of an ideal continuous line source.

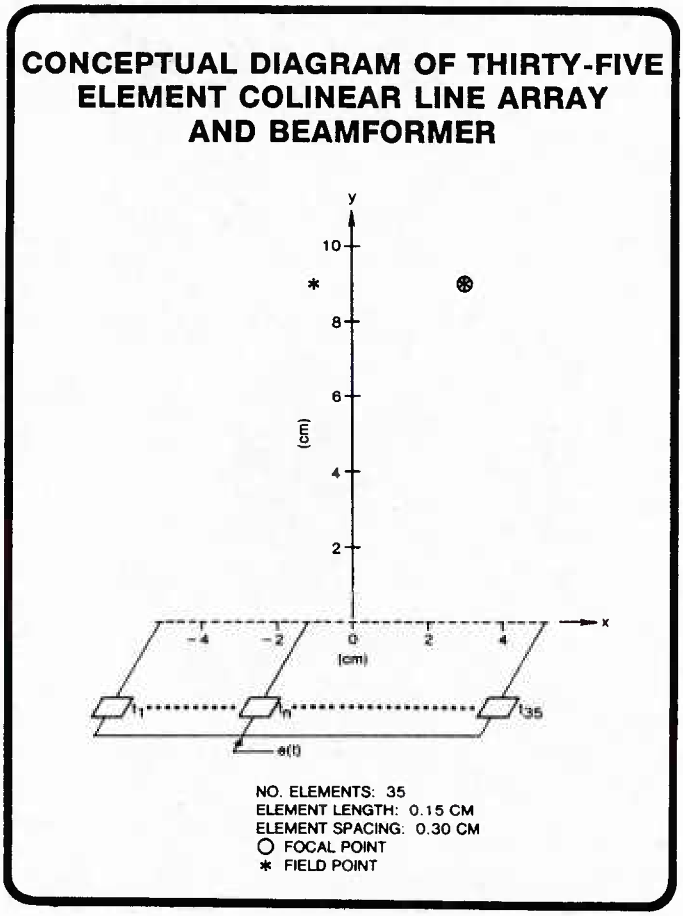
-- Next viewgraph, please (6). --



Viewgraph 6

Consider an array system composed of line elements and a time delay beamformer as shown in (a) of viewgraph 6. The individual elements are extended sources of length, L, for which the spatial impulse response can be represented as a boxcar function. The impulse response can be ideally delayed by the beamformer. As a simple example, consider the 5-element collinear array and beamformer illustrated here. If the beamformer, depicted here as parallelograms, is removed by setting all time delays (t_1 through t_5) to zero, the derivative of the transmit impulse response at the field point is as shown in (b). The strength of the positive and negative impulse pairs is determined by the distance between the center of the element and the x-coordinate of the field position. The location of each impulse in the time domain is determined by the element location and spatial extent, L. With the field point located directly above the second element, the impulses from elements 1 and 3 are collocated and simply summed using linear superposition as indicated by the stacked arrows in (b). When the beamformer is used to focus the array at the field point, the temporal spread caused by the element location with respect to the field point is removed. The temporal spread caused by the spatial extent of the elements still exists as in (c). That is to say, as expected, the directional characteristics of the elements are not removed. Therefore, if the total time spread of the array impulse response (shown in (c)) is small compared to the highest frequency component of the input time function and the pulse duration is greater than the impulse spread, a steady state solution approaching an ideal array output will be obtained from the convolution integral or impulse response approach.

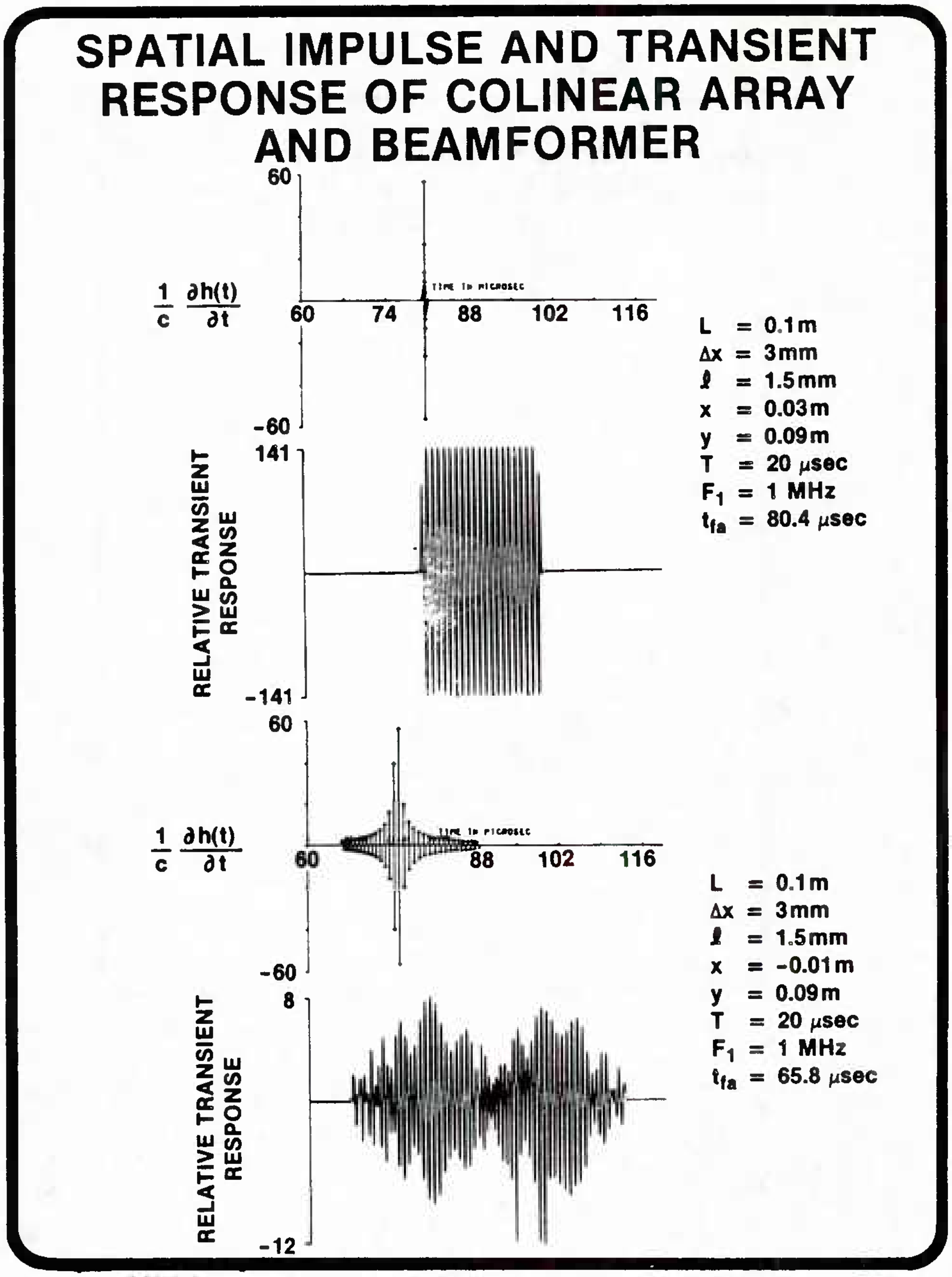
-- Next viewgraph, please (7). --



Viewgraph 7

The transmit transient response of more complex collinear arrays can now be examined. Consider the ultrasonic array system shown here. This 35-element array has an interelement spacing of 3 mm and element lengths are 1.5 mm, or one wavelength at 1 MHz. The array beamformer values, t_n, are set such that the the array is focused at the point indicated by the circle at x = 3 cm and y = 9 cm. We will now show the spatial impulse and normalized transient pressure response at the two points marked by asterisks.

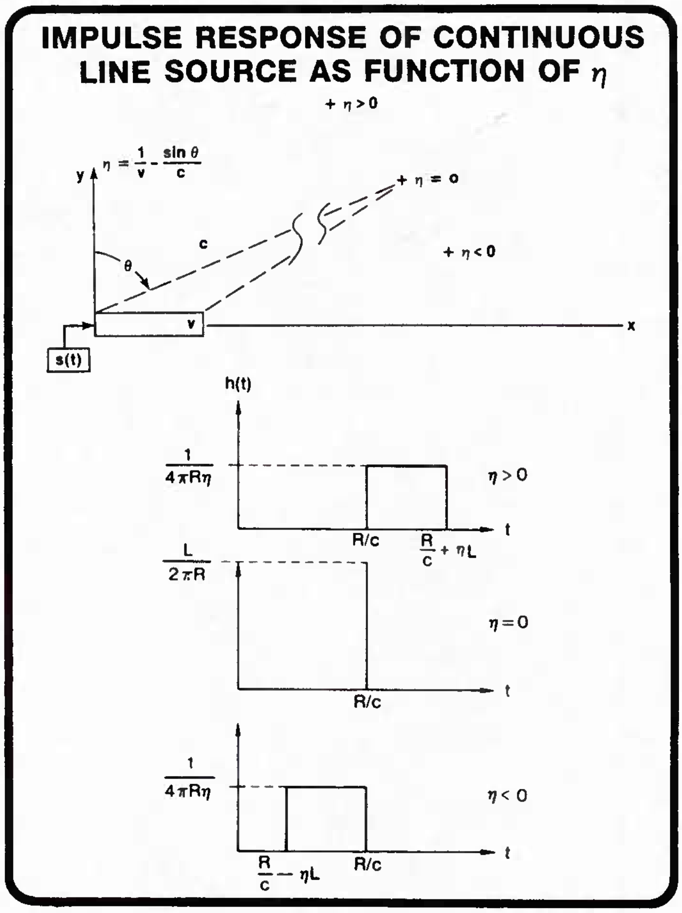
-- Next viewgraph, please (8). --



Viewgraph 8

The derivative of the impulse response at the focal point is shown in the upper figure. Note that the beamformer time delays have reordered the impulses so that they nearly coincide. The remaining temporal dispersion is due to the finite extent of the radiators. Large differences in the strength of the impulse pairs occur because the effects of spreading and element directivity are included in the impulse responses. The transient pressure response arising at this field point from a 20 μs, 1 MHz pulse is shown in the second part of the viewgraph. We see that the excitation waveform is recovered and a steady state solution is achieved. The spatial impulse response and corresponding pressure response due to a similar excitation at a field point other than the focal point are shown in the lower half of this viewgraph. We see the spatial impulse response is nearly 25 μs in duration and the impulses are spaced unequally. This results in temporal smearing and a complex interference in the pressure response function.

-- Next viewgraph, please (9). --

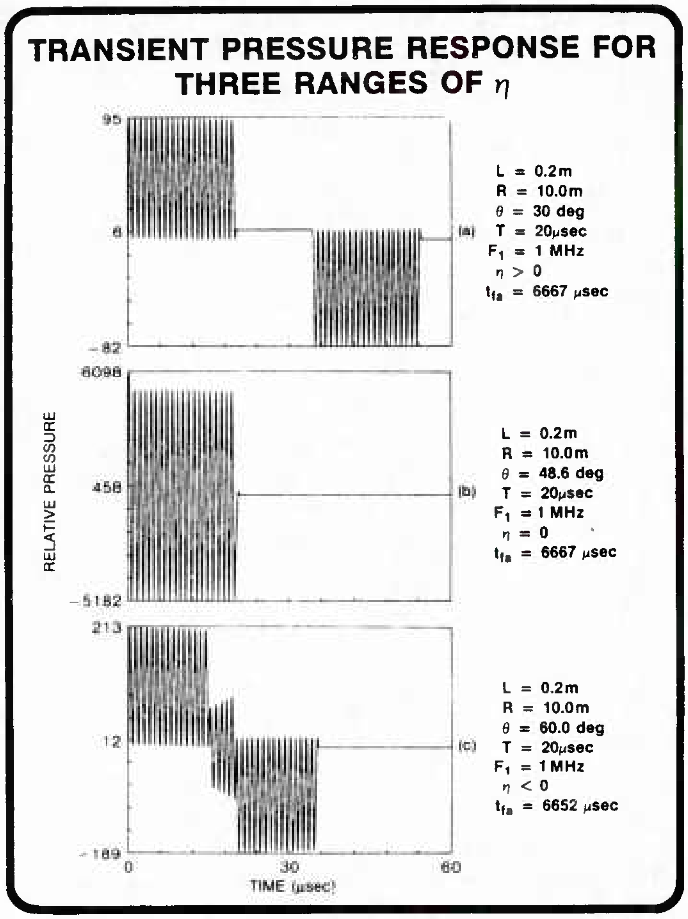


Viewgraph 9

For simplicity, the previous development for a continuous line assumed the source was uniformly excited. Now, consider a case of the more general impulse response where the excitation of each point is dependent on its position and the speed of propagation, v, down the source. This translates into a delay associated with the excitation function, which is spatially dependent on the source location. The speed, v, could be associated with the speed of electromagnetic propagation, the speed of a propagating wave in a different medium, or a well-designed delay line for a beamformer.

We now define a function, η, as shown in the upper left-hand corner of viewgraph 9. Let us examine the impulse response of this system for different values of η, which subdivides the field into regions with different characteristics for the impulse responses. When $\eta > 0$, the leading edge of the impulse arises from the source point farthest from the field point and the trailing edge location is dependent on the values of v, c, and θ. Thus, the path directly through the medium is the fastest. When $\eta < 0$, the reverse is true and the leading edge is dependent on v, c, and θ, so it is faster to travel down the source than through the medium to the field point. When $\eta = 0$, then $\sin \eta = c/v$, and, along this radial in the farfield, all elemental point sources contribute at the same time forming a single impulse at $t = R/C$. The significance of the result is that the proper delays required for beamforming can be obtained directly from the array impulse response function. We now examine the pressure responses for this system.

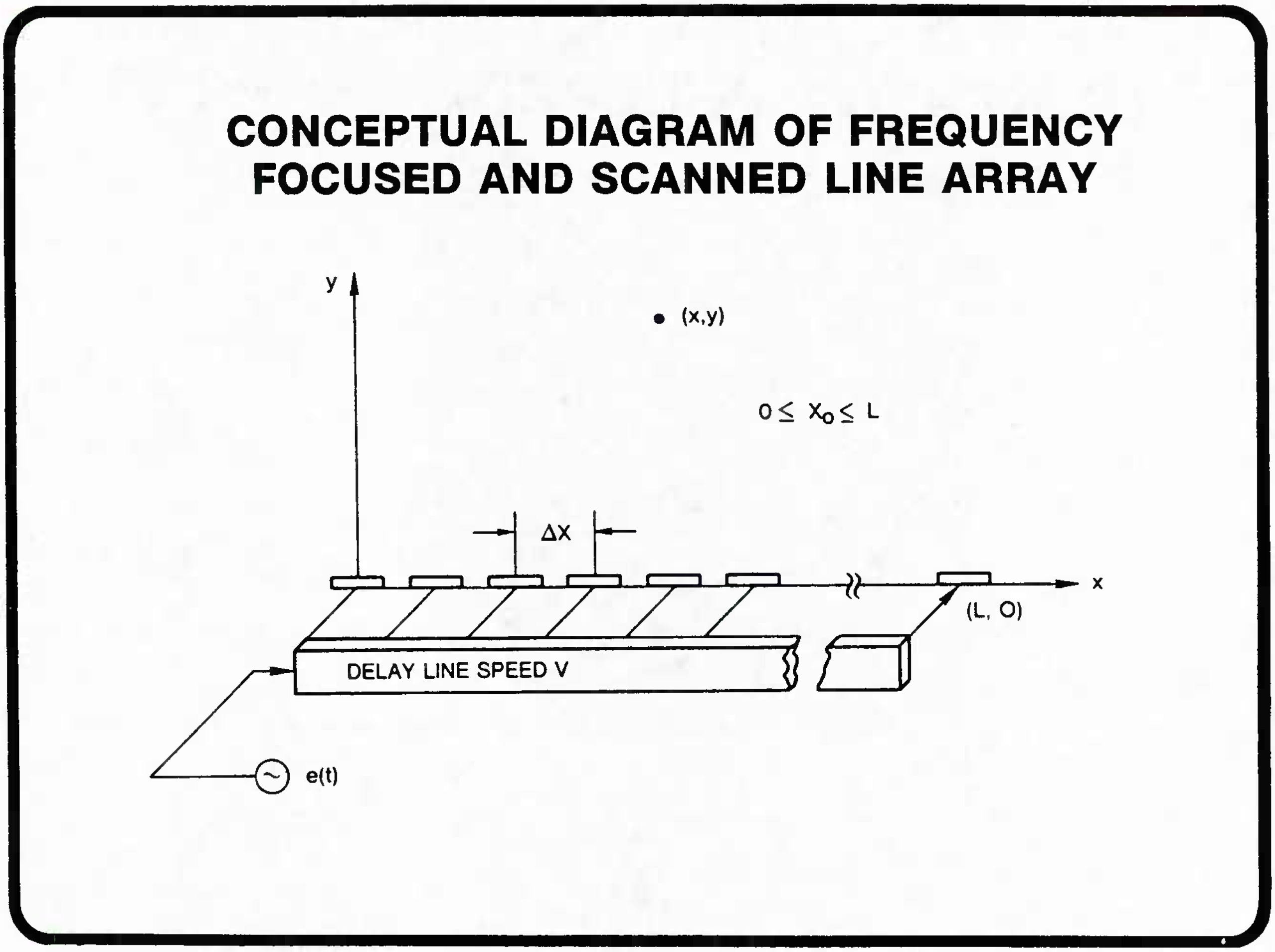
-- Next viewgraph, please (10). --



Viewgraph 10

Consider an example where the array length is 0.2 m and the delay line speed is 2000 m/s (as in (a)). The three field points of interest lie on the arc of a 10 m circle at bearings such that the three possible ranges of η are examined. The transient pressure response resulting from a 20 μs CW excitation pulse at each of the three field points is presented in viewgraph 10. When $\eta>0$, the time (t_{fa}) at which a disturbance first reaches the field point is associated with the end of the array located at the coordinate system origin. The transient duration is about 55 μs and a steady state pressure response is never achieved. In (b), the pressure function appears to be a near replica of the input signal as expected when $\eta = 0$. There is a transient effect near the beginning and end of the response, but, for the most part, this figure represents a steady state solution. The arrival time of the initial disturbance is as expected, i.e., the same as in the $\eta > 0$ case. Furthermore, it should be noted that the ratio of the pressure amplitudes shown in (a) and (b) is nearly 60:1. When $\eta < 0$, the initial disturbance arises from the end of the array nearest the field point. This means it is faster for a disturbance to travel through the array before entering the medium than to travel solely in the medium. The transient response begins at 6652 μs and lasts about 35 μs so that for the $\eta < 0$ case the end of the transient is the same as the beginning of the transient when $\eta > 0$. As in the case for $\eta > 0$, the amplitude of the transient is substantially less than in the case when $\eta = 0$.

-- Next viewgraph, please (11). --

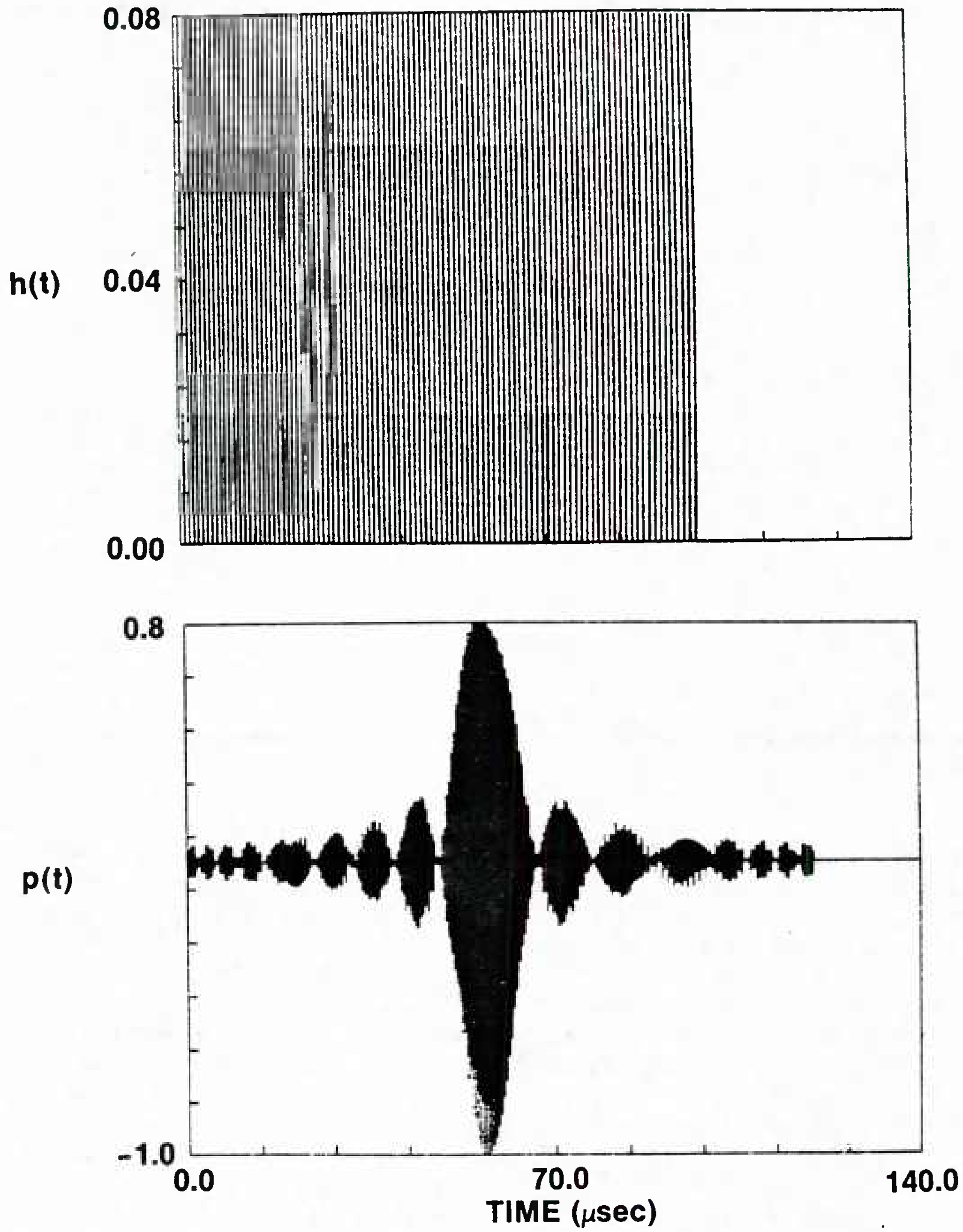


Viewgraph 11

A further application of the impulse response technique to a more complex array system is worthwhile. Consider an electronically focused and scanned line array. This type of array system, used in acoustic imaging, has been described by Kino and coworkers. They have shown a time-dependent frequency signal sent through a delay line can be used for the purpose of electronically focusing and scanning. This viewgraph illustrates the concept in an array system of this type. The initial excitation time of each element is delayed an amount determined by the delay line speed and element position. The element remains energized for the pulse length. Normally, the pulse length is less than the time required for a disturbance to transit the delay line. In effect this results in a subset of elements energized at any instant of time. This subset forms an active array that transits the array elements at speed, v, and is the basis of a scanned array. For focusing, a linear frequency modulation (LFM) chirp signal is used in practice as it is easily generated. The selection of the center frequency, which is dependent on the interelement spacing, Δx, and delay line speed, v, determines the azimuthal angle of the maximum beam while the LFM slide constant determines the focal range. The impulse response technique can be readily used to analyze the behavior of such complex array systems.

-- Next viewgraph, please (12). --

FARFIELD SPATIAL IMPULSE AND TRANSIENT PRESSURE RESPONSE



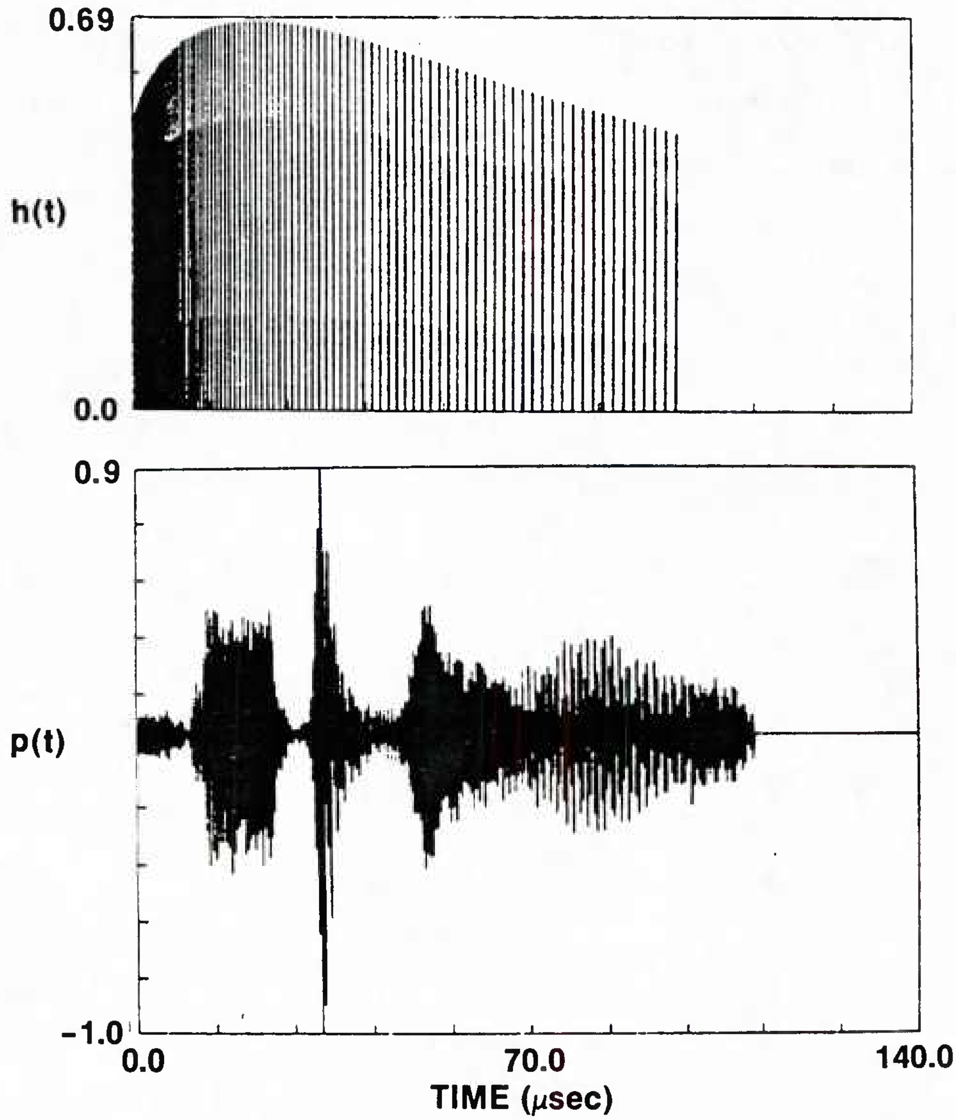
ARRAY LENGTH	–	0.2m
ELEMENT SPACING	–	0.002m
FOCAL RANGE	–	1.0m
MEAN FREQUENCY	–	2 MHz
PULSE LENGTH	–	20 μsec
t_{fa}	–	670 μsec

Viewgraph 12

Consider now an array of 100 equispaced elements when the focal range is large with respect to the entire array length, L. The impulse response for a typical field point is shown at the top of the viewgraph. For this case, the amplitude of each impulse will be nearly constant. Furthermore, the arrival time difference between each impulse is nearly, but not exactly, the same. Thus, for a sample point in the farfield, the focusing process is achieved with a CW pulse traveling down the array. The instantaneous transient pressure response obtained using the impulse response technique and the indicated variables are shown in the lower half of the viewgraph. The sinc dependence on time is expected. It can be noted that the ratio of mainlobe to first sidelobe is very near the expected value of 4.7, or equivalently 13.5 dB. Also of interest is the slight asymmetry of the response in time and amplitude because of aberration induced by the pulse traveling down the delay line.

-- Next viewgraph, please (13). --

SPATIAL IMPULSE AND TRANSIENT RESPONSE OF FREQUENCY FOCUSED AND SCANNED LINE ARRAY



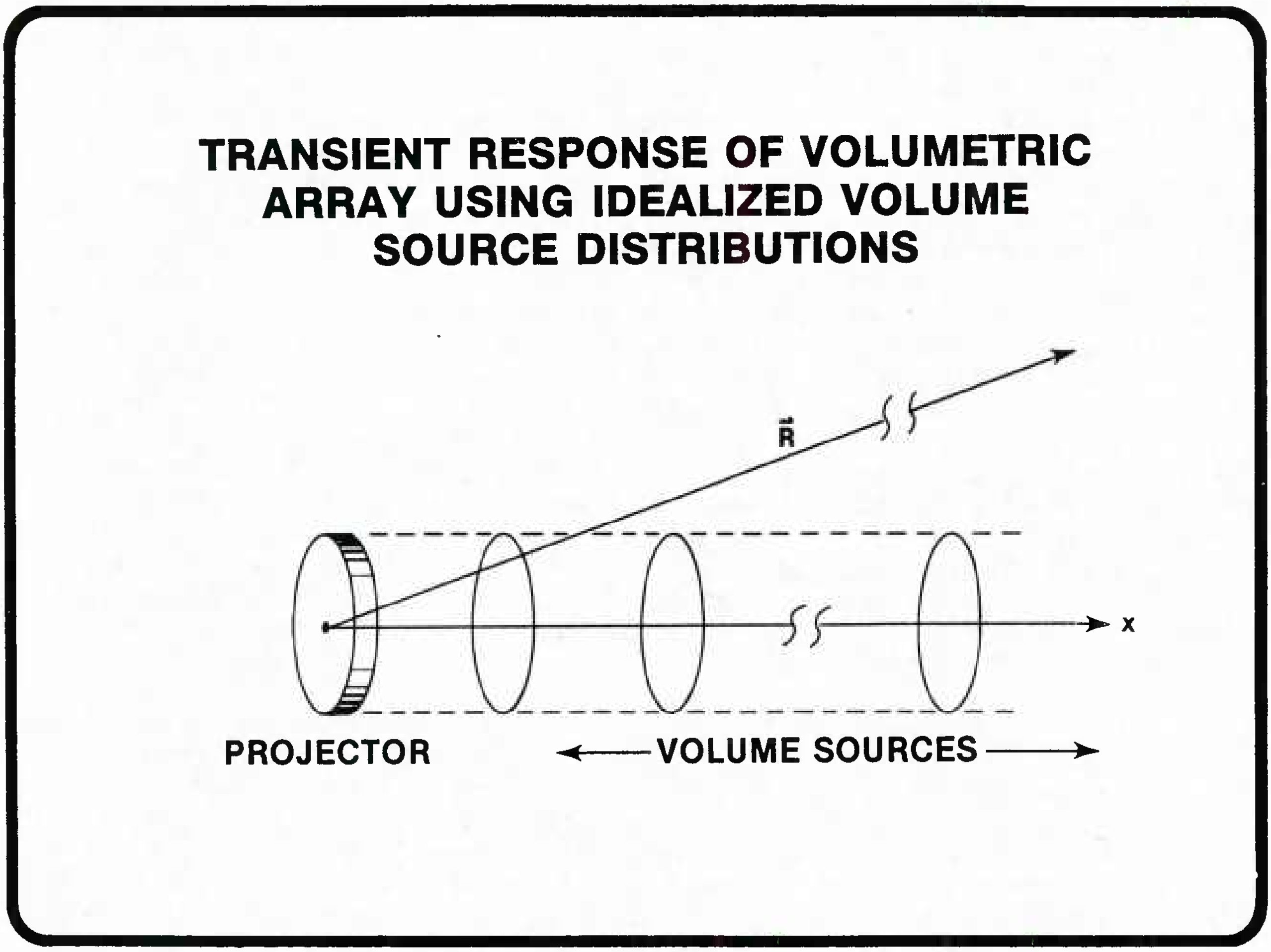
ARRAY LENGTH	–	0.2m
ELEMENT SPACING	–	0.002m
FOCAL RANGE	–	0.1m
MEAN FREQUENCY	–	2.0 MHz
PULSE LENGTH	–	20 μsec
t_{fa}	–	94 μsec

Viewgraph 13

Consider now a case when the field point is relatively close to the array, but still at a range such that each element behaves as a simple source. The strength of the impulse response arising from each element is quite simple, but its location in time relative to other elements is more complex. The impulse response for a 100-element array at a focal range of 10 cm is depicted in the upper part the viewgraph. In this particular case, the field point is located over the array midpoint. Thus, though difficult to see, there are as many impulses to the left as to the right of the maximum value. However, the temporal spread about the maximum value is not symmetrical. The exact frequency required to obtain the constant phase values needed for focusing can be readily obtained by determining the time between impulses. For a given pulse length, only a portion of the array is excited at any given time. If the exact frequency content required for focusing is replaced by an approximation (as in the case with an LFM chirp), then a reasonable facsimile of ideal focusing can be achieved. When the LFM signal dictated by this technique and containing a center frequency of 2 MHz is convolved with the impulses (as shown in the upper figure) and differentiated, the pressure field shown in the lower figure is obtained. It is clear that the array system is focused at the spatial point of interest about 32 μs after the initial arrival.

There are several other features in the transient pressure response that can be explained on the basis of the impulse response function. Note from the impulse response in the upper figure that the temporal samples are nonuniformly spaced in time. This is analogous to unequal element spacing. It is well known from antenna design theory that the radiation pattern of an aperiodic spatial array may be described in three parts. The maximum response region exhibits characteristics for which the array is designed. This is followed by a clean sweep region and then a region of moderately high levels called the plateau region. These regions are then analogous to the time domain response observed in the lower figure with a few complications. Observe that there is a maximum response at approximately 32 μs; there are regions of very low amplitude adjacent to the maximum response; and there is the resemblance of plateau regions near the beginning and end of the transient response. The picture is somewhat complicated because in this instance the amplitude response is dependent on time, and a moving pulse leads to nonsymmetrical results because of aberration.

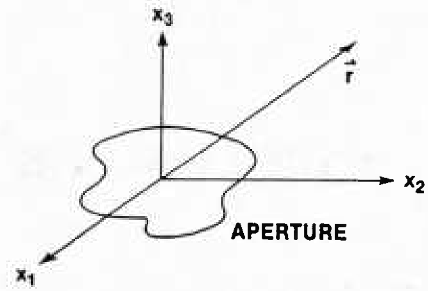
-- Next viewgraph, please (14). --



Viewgraph 14

As a final case of interest to illustrate the usefulness of the generalized impulse response approach, we note that the technique is readily applicable to evaluate the characteristics of the acoustic transient fields that are generated by idealized secondary source distributions, which are broadband. A specific example of interest is the case of a projector or transmitting array that is generating a highly directive finite amplitude broadband signal propagating along its axis as illustrated in the viewgraph. A theory to evaluate the on-axis transient pressure from such a transient parametric array was originally presented by Berktay and was later experimentally verified by Moffett and co-workers.

-- Next viewgraph, please (15). --



$$q(\vec{x}, t) = \begin{cases} w(x_3)\, s(t - x_3/c) & \vec{x} \in V_A \\ o & \text{OTHERWISE} \end{cases}$$

$$p(\vec{r}, t) = \varrho \frac{\partial}{\partial t} \left\{ s(t) * h_V(\vec{r}, t) \right\}$$

WHERE

$$h_V(\vec{r}, t) = h_L(\vec{r}, t) * h_A(\vec{r}, t)$$

WITH $h_L(\vec{r}, t)$ = IMPULSE RESPONSE FOR EQUIVALENT LINE SOURCE

$h_A(\vec{r}, t)$ = IMPULSE RESPONSE FOR APERTURE

Viewgraph 15

Without presenting the details of the development, which are omitted here because of time constraints, it is noted that the characteristics of transient pressure fields resulting from transient parametric arrays can be simply evaluated via the present impulse response approach. The edge diffraction effects are ignored in the source term, q, which is represented as a spatially decaying, one-dimensional, propagating wave in the cylindrical volume defined by the aperture as its base. The term $W(x_3)$ in the source term denotes the weighting of the source distribution in the x_3 direction, which for a transient parametric array would be exponential in nature. The farfield time-dependent pressure at any point resulting from the idealized source distribution can be expressed as a convolution of the source function s(t) with the impulse response $h_V(r,t)$. Finally, in the farfield it is noted that the volume impulse response can itself be expressed as a convolution of two impulse response functions as denoted on the viewgraph. These latter impulse responses correspond to the impulse responses for an equivalent line source, neglecting the aperture effect and for an aperture impulse response, neglecting the line effect. It is noted that the convolution of the impulse responses to obtain $h_V(r,t)$ is the time domain equivalent of the usual product theorem in array analysis and could have been anticipated apriori.

-- Last viewgraph, please (16). --

CONCLUSIONS

- THE IMPULSE RESPONSE TECHNIQUE IS A VIABLE APPROACH FOR ANALYZING COMPLEX ARRAY BEAMFORMING SYSTEMS SUBJECT TO STEADY STATE AND TRANSIENT EXCITATIONS.
- THE TIME HISTORY OF SIGNALS GENERATED OR RECEIVED BY SUCH ARRAY SYSTEMS CAN BE STRONGLY AFFECTED BY THE SYSTEM.
- THE IMPULSE RESPONSE TECHNIQUE CAN BE USED TO EVALUATE TRANSIENT RADIATED FIELDS FROM IDEALIZED VOLUMETRIC SOURCE DISTRIBUTIONS.

Viewgraph 16

An approach has been developed to analyze the transmit response of complex arrays with time delay beamformers. This approach is based on an extension of the spatial impulse response developed by Stepanishen.

The impulse response technique is a viable approach to the formidable problem of analyzing array systems subject to transient excitations. The technique yields a spatial impulse response that is dependent on the geometry of the problem and beamformer. The impulse response can then be convolved with a variety of signal waveforms to perform an array systems analysis as a function of waveform design. This approach, therefore, can be used to conduct a rather complete systems analysis.

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